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Reduced sediment transport in the Chinese Loess Plateau due to climate change and human activities

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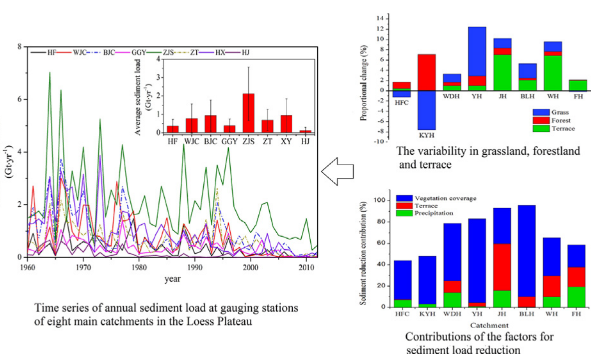
HIGHLIGHTS

- The sediment discharge in eight catchments located in the Loess Plateau showed a significant decrease since the 1960s.
- Sediment discharge in most tributaries had shown abrupt changes since 1996.
- The contribution of runoff reduction was greater than the sediment concentration change to the reduced sediment load.
- Increasing vegetation coverage was the primary factor driving the reductions in sediment loads.

GRAPHICAL ABSTRACT



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ABSTRACT

The sediment load on the Chinese Loess Plateau has sharply decreased in recent years. However, the contribution of terrace construction and vegetation restoration projects to sediment discharge reduction remains uncertain. In this paper, eight catchments located in the Loess Plateau were chosen to explore the effects of different driving factors on sediment discharge changes during the period from the 1960s to 2012. Attribution approaches were applied to evaluate the effects of climate, terrace, and vegetation coverage changes on sediment discharge. The results showed that the annual sediment discharge decreased significantly in all catchments ranging from -0.007 to -0.039 $Gt \cdot yr^{-1}$. Sediment discharge in most tributaries has shown abrupt changes since 1996, and the total sediment discharge was reduced by 60.1% during 1997–2012. We determined that increasing vegetation coverage was the primary factor driving the reductions in sediment loads since 1996 and accounted for 47.7% of the total reduction. Climate variability and terrace construction accounted for 9.1% and 18.6% of sediment discharge reductions, respectively.

1. Introduction

Soil erosion and the resulting river sediment transport are globally widespread and constitute a major environmental threat to human-managed ecosystems (Pimentel and Kounang, 1998). Soil erosion causes water pollution, water storage capacity reduction, and regional poverty, which is a challenge for sustainable social-economic

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development (Munodawafa, 2007; Zhao et al., 2013; Rickson, 2014). In recent decades, significant decreasing trends in river sediment loads have been observed in different parts of the world (Walling and Fang, 2003; Wang et al., 2015). A better understanding of the changes in river sediment loads over time and the driving mechanisms are thus of paramount importance for decision makers and planners to take appropriate sustainability measures. In general, climate change and human activities are two primary factors that affect soil erosion and the terrestrial hydrological cycle (Syvitski et al., 2005; Li and Fang, 2016; Li et al., 2016).

The impacts of climate change on soil erosion have been observed since the 1940s (Bryan and Albritton, 1943; Schumm and Langbein, 1958; Li and Fang, 2016). Mainly, the variety of rainfall amounts, intensities, and spatial distributions directly alter the erosion process. Lu et al. (2013) found that every 1% change in precipitation could result in a 2% change in sediment loads. Zhang (2007) suggested that a 4–18% increase in precipitation would lead to a 31–167% increase in soil loss. These findings show that soil erosion increases with increased precipitation when other factors remain unchanged. However, decreased soil erosion under increased precipitation has occurred in different areas of the world (Li and Fang, 2016), which may be attributed to land use/cover changes, reservoir and dam construction, and other human activities (Gao et al., 2011; Nunes et al., 2013).

Land use is one of the most important factors affecting the intensity and frequency of soil erosion (Wei et al., 2007; Garcia-Ruiz, 2010; Li et al., 2016). The main causes of soil erosion are inappropriate agricultural practices, deforestation, and urban construction. Soil erosion of agriculture land is widespread around the world (Collins et al., 2001; Garcia-Ruiz, 2010; Nunes et al., 2011). The integration of agricultural land use with shrubs, trees and grass can improve soil properties, surface roughness and evapotranspiration, thereby reducing sediment discharge into rivers (Cao et al., 2011; Wang et al., 2015; Zuo et al., 2016). Many authors have also demonstrated that in a wide range of environments, sediment loss decreases exponentially as the percentage of vegetation cover increases (Zhao et al., 2013; Wang et al., 2015). Terraces are another measure used to reduce slope erosion by weakening rainfall–runoff erosivity, conserving abundant rainwater, and increasing soil moisture. Evidence has shown that if terraces cover over 40% of a total hill slope, considerable soil load reduction could be achieved (Chen et al., 2017). Other studies have reported that terrace construction could reduce soil loss by >90% (He et al., 2009; W. Wei et al., 2016; Y. Wei et al., 2016). For decreasing the sediment load of river, check dams are another effective measure to intercept upstream sand and trap sediment, and these methods have applications in France, Italy, Spain, China and elsewhere (Boix-Fayos et al., 2007; Boix-Fayos et al., 2008; Abedini et al., 2012; Jin et al., 2012). More than 70% of the world's rivers have been reported to be intercepted by dams, and at least half of the river sediments may be trapped in artificial dams and reservoirs (Zhao et al., 2017)

The Loess Plateau, which loses approximately 5000–10,000 $t \cdot km^{-2} \cdot yr^{-1}$ of sediments in most areas and >15,000 $t \cdot km^{-2} \cdot yr^{-1}$ in some areas, is one of the most critical areas of soil erosion globally. The Yellow River is the most sediment-laden water body in the world (Pont et al., 2002; Wang et al., 2015), of which 90% of the sediment is contributed from the Loess Plateau (Zhao et al., 2013). More attention is being focused on reducing soil erosion, maintaining soil fertility, and a healthy Yellow River. Since the 1950s, a series of measures were implemented in the Loess Plateau to reduce the sediment discharge into the river (Wang et al., 2007b). Terrace and dam construction was the main measure in the 1960s and 1970s. Then, in the 1970s, integrated catchment management was applied to reduce soil erosion. At the beginning of the twenty-first century, in order to control increasingly serious soil and water loss, the Chinese government launched a large-scale ecological restoration project named “Grain for Green Program” (GfG) (Su et al., 2011). The sediment load of the Yellow River has decreased by approximately 90% over the past six decades (Wang et al., 2015). Many scholars suggest that soil and water conservation measures were responsible for the sediment load reduction in the middle reaches of the Yellow River (Zhao et al., 2014). Gao et al. (2011) estimated that the decrease in human activities accounted for 87.8% of the decrease in sediment discharge from 1982 to 2008, whereas Mu et al. (2012) showed that a decrease in human activities accounted for 81% of the sediment discharge reduction in the Yellow River basin during 1979–2008. However, the quantitative research on the causes of decreases in sediment load by each measure such as land use/cover changes and terraces still face challenges, especially at larger scales.

The main aims of the present study were to evaluate the contribution of climate change and human activities to sediment load reduction in eight catchments in the Loess Plateau. Our specific objectives were to (1) investigate the spatial and temporal variations in sediment load in the catchments and (2) quantify the anthropogenic and climatic contributions to changes in sediment load.

2. Materials and methods

2.1. Study area

The Loess Plateau lies in the upper and middle reaches of the Yellow River basin in North China (between 33°43′–41°16′N, 100°54′–114°33′E), which covers 62.4×10^4 km^2 of China's total land area with approximately 8.5% of the Chinese population distributed in this region (Zhao et al., 2013). The Loess Plateau is characterized by a temperate arid to semi-arid climate with a mean annual temperature ranging from 4.3 to 14.3 °C and an annual rainfall from 200 to 750 mm, of which 65% falls between July and September (Wang et al., 2017). The average annual evaporation was between 1400 and 2000 mm. The altitude varies between 200 and 3000 m above sea level, and the average elevation is 1212 m. The middle reaches of the Yellow River, between Toudaoguai and Huayuankou, cross the Loess Plateau (Fig. 1). There are >30 large tributaries in the Loess Plateau that contribute approximately 90% of the sediment to the Yellow River. The main tributaries from north to south, such as Huangfuchuan, Kuyehe, Wudinghe, Yanhe, Beiluohe, Jinghe, Weihe, and Fenhe, are chosen as the study region in this research (Table 1).

2.2. Data sources

The Yellow River Conservancy Commission (YRCC) provided annually observed streamflow, and sediment load data at the main gauging station along eight tributaries of the Loess Plateau (1960–2012). Meteorological data from seventy-two weather stations in the Loess Plateau from 1960 to 2012 were obtained from the China National Meteorological Information Center (http://cdc.cma.gov.cn/home.do). The interpolation method of GIDS (gradient plus inverse distance squared) for the weather station was applied to obtain the watershed climate information. Records of soil and water conservation measures at the county scale for 1990 and 2010, which include terraces, dams and reservoirs, were provided by the China water census and the National Earth System Science Data Sharing Infrastructure (http://loess.geodata.cn/). Land use data with spatial resolution of 30 m for 1990 and 2010 were provided by the Chinese Academy of Sciences Resource and Environment Science Data Center. Vegetation coverage was extracted by the normalized difference vegetation index (NDVI) derived from long-term data record (AVH13C1) at a spatial resolution of 8 km for the period of 1981–1999 and the moderate resolution imaging spectroradiometer (MOD13A3) with 1 km resolution from 2000 to 2012. The area of water soil erosion in different levels for 1990 and 2010, which are county-scale statistics, were provided by the China Water Census; Table 2 shows the different levels corresponding to the average amount of erosion and loss of depth in the Loess Plateau, which were classified according to the Standards for classification and gradation of soil erosion (MWR, 2008; Wang et al., 2016).

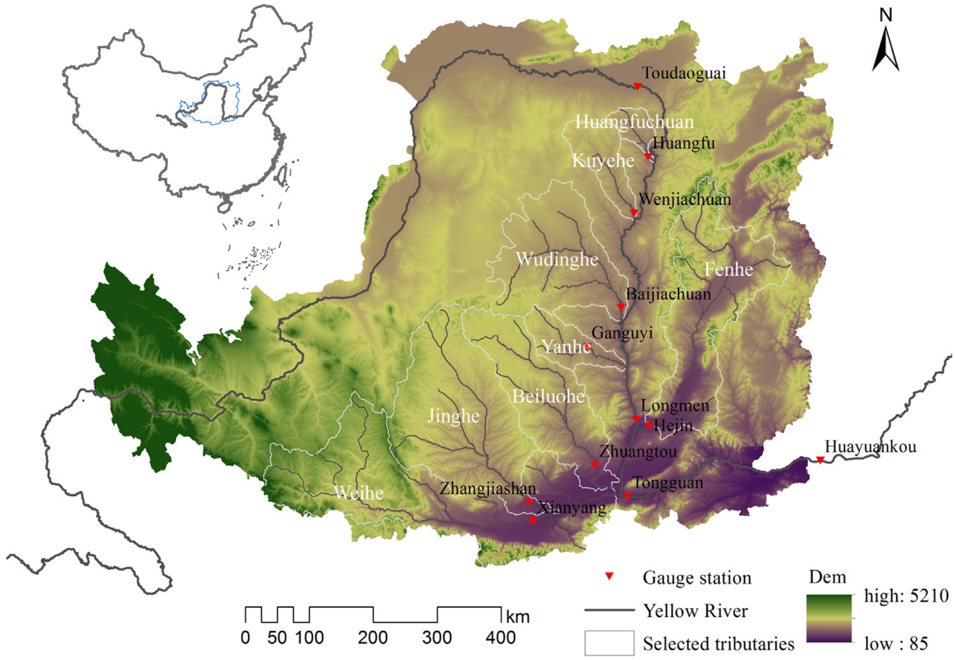

Fig. 1. Location of the Loess Plateau and the main catchment in the middle reaches of the Yellow River. The white shapes depict the boundary of selected tributaries. The red triangle represents the gauging station for the tributaries and mainstream of the Yellow River. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.3. Evaluating the effects of precipitation on sediment

The double mass curve, which is one method for comparative analyses, is widely used to quantitatively evaluate the influence of climate change or anthropogenic activity on streamflow (sediment) (Gao et al., 2017). The double mass curve exhibits a straight line if the proportionality of two variables remains unchanged. A break in the slope of curve may indicate that a change in the characteristics of the climate, sediment, or streamflow occurred (Gao et al., 2011; Li et al., 2016). In this study, the information on precipitation vs. sediment discharge was plotted for the two periods, and the pre-change period was used to establish the linear regression equations. The mean precipitation of the post-change period was used in these regression equations, and the mean annual sediment discharge of the post-change period without the effects of human activities were extrapolated (Li et al., 2016). Then, the impact of climate change and human activities on sediment discharge can be calculated as follow:

$$\Delta S_{hum} = S_{ao} - S_{ac} \quad (1)$$

$$\Delta S_{pre} = S_{ac} - S_{po} \quad (2)$$

where ΔS_{hum} denotes the change in the mean sediment discharge due to the effect of human activities (ton); S_{ao} and S_{ac} refers to the observed and calculated sediment discharge of the post-change period extrapolated using the regression equation for the pre-change period (ton). ΔS_{pre} represents the change in the mean annual sediment discharge due to the effect of climate change (ton); S_{po} is the observed sediment discharge of the pre-change period (ton) (Li et al., 2016).

2.4. Contribution assessment of terraced field measures

Water balance equations and hydrological models have been used to assess the contribution of climate change and human interventions to sediment discharge changes (Zhao et al., 2014; Gao et al., 2017). Although the water balance equations and hydrological models can provide accurate results, large numbers of parameters and input datasets were difficult to obtain. It is also difficult for these models to apply over large areas, particularly those subject to data deficiencies. Additionally, there are few hydrological models with a terrace module for large scales. Thus, the regression model was used between the terrace density and sediment reduction rate. For the description of the terraced field scale, the regression model introduced the concept of the 'terraced proportion', which refers to the proportion of terraced area to the area of mild soil erosion area. The data for approximately 26 places of terraces and sediment load during the 1970s were used to obtain the relationship between the terraced proportion and the sediment reduction. Those data focused on the places where there were almost no vegetation changes, the rainfall amount and intensity were similar, and only the terraces had changed. The relationship between the percentage of terraced area and sediment reduction are shown in Fig. 2 (Liu et al., 2014). The model verification error is <8% in the upper reaches of the

Table 1
The location of hydrological stations.

Catchment	Station	Control area (km^2)	Longitude (E)	Latitude (N)
Huangfuchuan	Huangfu	3175	39°17′	111°02′
Kuyehe	Wenjiachuan	8515	38°26′	110°45′
Wudinghe	Baijiachuan	29,662	37°14′	110°25′
Yanhe	Ganguyi	5891	36°42′	109°48′
Jinghe	Zhangjiashan	43,216	34°38′	108°36′
Beiluohe	Zhuangtou	25,154	35°02′	109°50′
Weihe	Xianyang	46,828	34°19′	108°42′
Fenhe	Hejin	38,728	35°34′	110°48′

Table 2
Classes for water soil erosion intensity in the Loess Plateau.

Level	Average amount of water erosion ($t \cdot km^{-2} \cdot yr^{-1}$)	Water erosion depth ($mm \cdot yr^{-1}$)[a]
Light	1000–2500	0.74–1.9
Moderate	2500–5000	1.9–3.7
Intensive	5000–8000	3.7–5.9
Very intensive	8000–15,000	5.9–11.1
Severe	>15,000	>11.1

[a] Average loss thickness was converted using a soil bulk density of 1.35 g/cm^3.

Weihe and Jinghe (Liu et al., 2014). The model calculation is as follows:

$$T_i = 100 \times \frac{A_t}{A_{re}} \quad (3)$$

$$W_s = 93 - \frac{93}{1 + (T_i/13.2)^{2.6}} \quad (4)$$

where W_s refers to the percentage contribution to sediment load reduction (%), and $R^2 = 0.93$; T_i refers to the terraces proportion (%); A_t and A_{re} refer to the area of horizontal terraces and mild soil erosion, respectively.

2.5. Contribution assessment of human restoration measures

We introduce linear relationships between the vegetation coverage and runoff coefficient ($y = -0.048x + 4.56$, $R^2 = 0.72$; x and y refer to vegetation coverage (%) and runoff coefficient (%)) and flow sediment concentration ($y = -5.94x + 657.28$, $R^2 = 0.74$; x and y refer to vegetation coverage (%) and sediment concentration ($kg \cdot m^{-3}$)), which was developed by Wang and his colleague (2015). The runoff coefficient, suspended-sediment concentration, and vegetation coverage data are for fifteen catchments in the Loess Plateau, such as Huangfuchuan, Kuyehe, Yanhe, and Beiluohe. The analysis of the data focused on catchments that had the least number of dams, reservoirs, and terracing during the research period. Then, we calculated the contribution of vegetation coverage increase to the water discharge and sediment yield for eight tributaries.

3. Results

3.1. Changes in sediment load from 1960 to 2012

A total of 6.18 $Gt \cdot yr^{-1}$ of sediment from eight tributaries flows into the middle of the Yellow River, between the Toudaoguai gauging station (0.07 $Gt \cdot yr^{-1}$) and the Tongguan station (0.63 $Gt \cdot yr^{-1}$), which is the main reason for the high sediment yield of the Yellow River. For the tributaries, the Jinghe contributes the most, representing 33.2% of the total sediment transport, and the least amount of sediment discharge is recorded at the Hejin station, with just 0.12 $Gt \cdot yr^{-1}$ (Fig. 3). Since 1960, the annual sediment discharge showed a reduction over the entire study area (Fig. 3). The total annual sediment loads of all gauging stations exhibited a decreasing trend of -0.180 $Gt \cdot yr^{-1}$ ($p < 0.0001$). The annual sediment loads showed significant decreasing trends ($p < 0.01$) at most gauging stations except Zhangjiashan ($p = 0.017$) over the past five decades. The rate of changes in sediment loads varied from -0.007 to -0.039 $Gt \cdot yr^{-1}$, and the Xianyang, Zhangjiashan, and Baijiazhuan stations decreased the most, with average reduction rates of -0.039 $Gt \cdot yr^{-1}$, -0.036 $Gt \cdot yr^{-1}$ and -0.032 $Gt \cdot yr^{-1}$, respectively. The sediment loads at Hejin and Ganguyi showed more gently decreasing trends, with average decrease rates of -0.007 $Gt \cdot yr^{-1}$ and -0.009 $Gt \cdot yr^{-1}$, respectively.

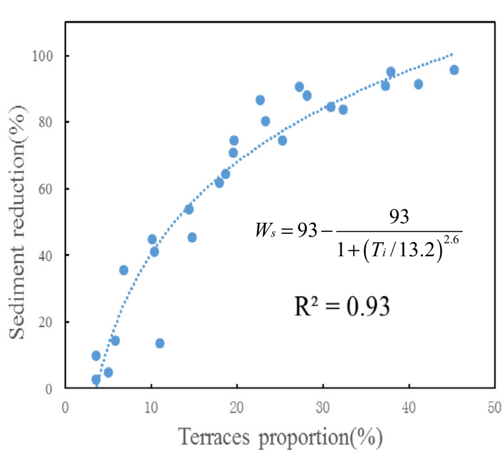

Fig. 2. The relationship between percentage of terraced area and sediment reduction.

3.2. Change-point analysis for sediment regimes

To quantify the sediment load changes before and after the transition years, double mass curves were plotted to show the correlation between the cumulative annual sediment load and precipitation. As Fig. 4 shows, there was one abrupt drop in sediment load around 1996 in all the tributaries; however, some tributaries show two abrupt drops over the past five decades. Thus, we divided the analysis into two periods, which covered 1980–1996 (P1) and 1997–2012 (P2), and mainly focused on the sharp sediment decrease phenomenon that occurred after 1996 in the entire study area. The analysis showed a pronounced decrease in sediment load from 5.92 $Gt \cdot yr^{-1}$ during P1 to 2.36 $Gt \cdot yr^{-1}$ during P2 for the total sediment load of all tributaries (Table 3). Among the main tributary catchments, the Fenhe showed the greatest decrease (94.6%), despite having the lowest sediment load, and all were reduced by >40%. The Huangfuchuan and Kuyehe seemed to be more successful in protecting the soil, as the reductions in sediment loads were 70%. Only the Jinehe's rates of sediment reduction were <50%. The Jinghe contributed a large sediment load to the Yellow River from 37.4% during P1 to 47.8% during P2 and contributed the most with 30.5% reduced sediment for the Yellow River.

3.3. Contribution of runoff and sediment concentration variability to sediment load reduction

The decrease in sediment load is due to changes in runoff and sediment concentration, and these changes are affected by regional climate changes and human activities. In the whole study area, the annual runoff decreased significantly, with the average annual rate of decrease being from -0.020 to -0.278 Gm^3 ($p < 0.01$) over the past five decades. Sediment concentration showed a similar decrease, and the changes varied from -0.001 to -0.003 $t \cdot m^{-3} \cdot yr^{-1}$. The total annual runoff and average sediment concentration showed a sharp reduction by 29.03 Gm^3 and 0.07 $t \cdot m^{-3}$ from P1 to P2, representing 33.9%, and 60.7%, respectively (Table 3). We estimated that runoff reduction contributed to the reduced sediment load by 2.1 Gt (59.6%) and that the sediment concentration contributed to the reduced sediment load by 1.4 Gt (40.4%) between P1 and P2. Among the main tributary catchments, the Huangfuchuan and Kuyehe showed sharp reductions in runoff, with reduction rates of up to 65.1% and 61.4%. For sediment concentration, the greatest reduction was detected in the Beiluohe catchment, which contributed to the reduced sediment load by 70.5% (Fig. 5).

3.4. Effects of climate variability on sediment load

The mean annual precipitation showed an increase from south to north, with the highest in Weihe (505.6 mm) and lowest in Huangfuchuan (379.3 mm), and all tributaries exhibited negative trends over the past five decades. From 1980 to 2012, the precipitation in all tributaries also exhibited negative trends, with rates of decrease ranging from -2.6 $mm \cdot yr^{-1}$ to -0.4 $mm \cdot yr^{-1}$. Significant downward trends were detected in the Yanhe, Jinghe and the Weihe from P1 to P2 (Table 3). We estimated that precipitation contributed to the reduced sediment load by 0.3 Gt, accounting for 9.1% between P1 and P2 (Fig. 6). Among the tributary catchments, the climate variability had a greater effect on the sediment load reduction in Jinghe (16.0%), Wudinghe (14.1%), and Fenhe (19.3%). The results indicated that precipitation variety accounted for little of the sediment load changes during P2 in all tributaries.

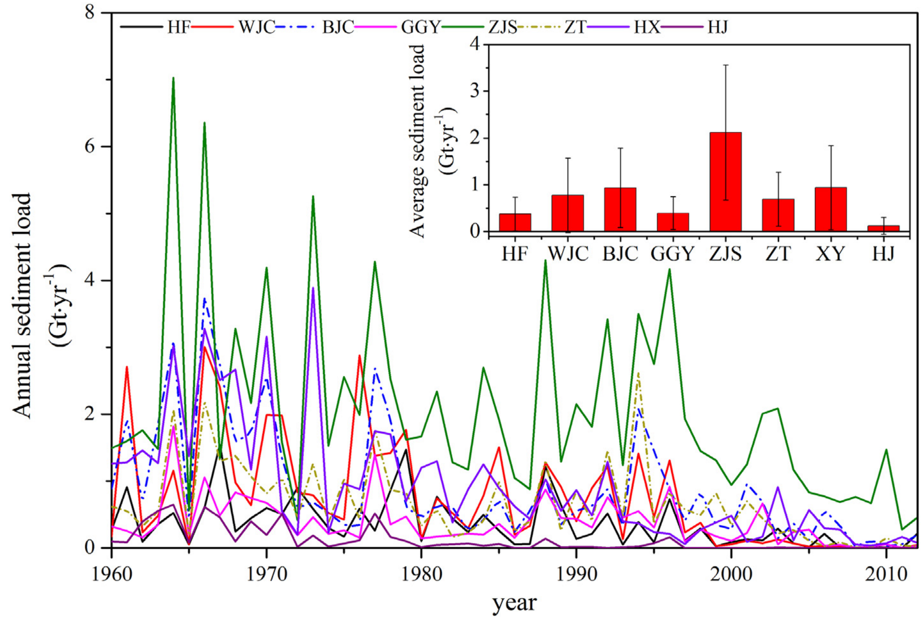

Fig. 3. The time series of annual sediment load at gauging stations in the Loess Plateau. Inset: the average annual sediment load from 1960 to 2012 at gauging stations in the Loess Plateau. HF, Huangfu; WJC, Wenjiachuan; BJC, Baijiachuan; GGY, Ganguyi; ZJS, Zhangjiashan; ZT, Zhuangtou; HX, Huaxian; HJ, Hejin.

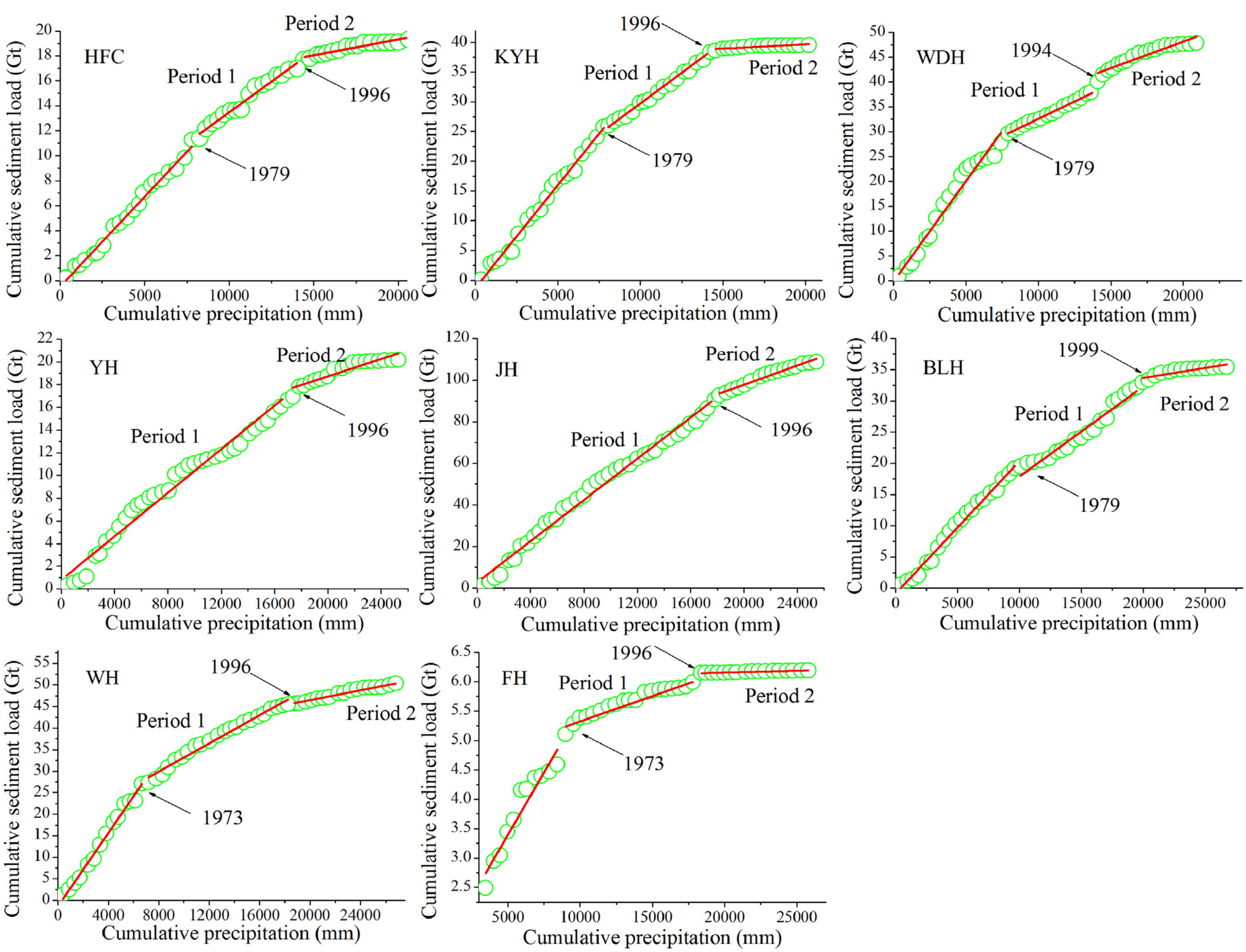

Fig. 4. Double mass curve analysis of the sediment load and precipitation in different catchments. HFC, Huangfuchuan; KYH, Kuyehe; WDH, Wudinghe; YH, Yanhe; JH, Jinghe; BLH, Beiluohe; WH, Weihe; FH, Fenhe.

Table 3
The average annual runoff, sediment load and effects of climate variability and human activities on sediment loads in the catchments over both periods. The terrace, forest, and grassland data were from 1990 and 2010.

Catchment	Period	Sediment load (Gt)	Runoff (Gm^3)	Precipitation (mm)	Terrace (km^2)	Forestland (km^2)	Grassland (km^2)
Huangfuchuan	P1	0.38	1.17	379.5	29.1	151.0	2477.3
	P2	0.10	0.41	366.4	42.0	194.5	2437.2
Kuyehe	P1	0.74	5.18	379.7	78.7	441.6	6339.0
	P2	0.08	2.00	372.9	84.8	1054.7	5679.8
Wudinghe	P1	0.71	10.21	385.9	1183.5	925.5	15,728.1
	P2	0.38	7.75	379.1	1483.3	1136.1	16,210.0
Yanhe	P1	0.41	2.17	488.0	270.7	1403.9	3961.0
	P2	0.16	1.43	464.1	349.1	1549.5	4694.1
Jinghe	P1	2.21	37.52	494.5	2396.0	9624.7	14,258.8
	P2	1.24	24.19	473.8	5594.1	10,216.6	15,108.1
Beiluohe	P1	0.70	7.60	524.2	572.6	10,963.0	7783.2
	P2	0.31	6.22	511.8	1142.6	11,071.0	8533.4
Weihe	P1	0.73	6.45	524.6	4300.9	11,333.6	4570.4
	P2	0.27	4.24	502.2	6807.8	11,689.1	5420.3
Fenhe	P1	0.04	15.41	493.7	1043.0	10,744.2	11,195.0
	P2	0.00	10.46	463.1	1851.7	10,788.9	11,128.5

3.5. Effects of human activity variability on sediment load

Terraces are human measures that reduce slope soil erosion and simultaneously increase the arable land yield. In this study, the average area of terraces increased from 4.3% in 1990 to 7.6% in 2010. Between P1 and P2, terraces contributed to the reduced sediment load by 0.7 Gt, accounting for 18.6%. As Fig. 7 shows, all catchments have developed terraces from P1 to P2. Weihe and Jinghe increased by 3.7% and 7.0%, respectively, and contributed to the reduced sediment load by 0.1 Gt and 0.5 Gt, respectively (Fig. 6). In terms of the spatial distribution, the terraces showed a decrease from south to north, and the Kuyehe and Huangfuchuan catchments had little effect on the reduction in the sediment load from P1 to P2.

A significant shift in the catchment pattern of land use has taken place from 1990 to 2010 (Table 3). With the GfG launched in 1999, the area of forest and grass shows an increase in most tributaries, increasing by approximately 5111.5 km^2 (accounting for approximately 2.2% of the total area). Grassland is the most commonly distributed land use type in the Yanhe, Wuding, Kuyehe and Huangfuchuan catchments, and forest land is distributed in the southern catchment (Table 3). Although grassland was decreased in Kuyehe, Wuding and Fenhe, the increasing forestland increased the vegetation coverage from P1 to P2 (Fig. 8). Modis data indicated that the average vegetation coverage of the eight main catchments increased from 28.4% in P1 to 41.4% in P2. Approximately 47.7% (1.7 Gt) of the reduction in the average sediment load between P1 and P2 resulted from the increased vegetation coverage. The vegetation coverage increase was the main reason for the sediment discharge reduction except for Jinghe and Fenhe (Fig. 6). Among the tributary catchments, Beiluohe showed the greatest increase in vegetation coverage because of the increases in forest and grasslands, which reduced the sediment load by 0.4 Gt.

Most human activities for catchment management were distributed in Yanhe and Jinghe during P2 in terms of terrace farming and GfG (Fig. 9). Different measures are used to control the soil erosion in catchments, and human activities have mainly caused the reduction in sediment in the middle reaches of the Yellow River. In total, for the increase in perennial vegetation coverage, terrace farming accounted for 66.3% of the sediment load reduction in tributaries across the Loess Plateau during P1 and P2, which is greater than the precipitation decrease of 9.1%. The key gully soil and water conservation project, check dams and other uncertainties, such as water consumption and river sand mining, contributed to the rest of the observed sediment reduction.

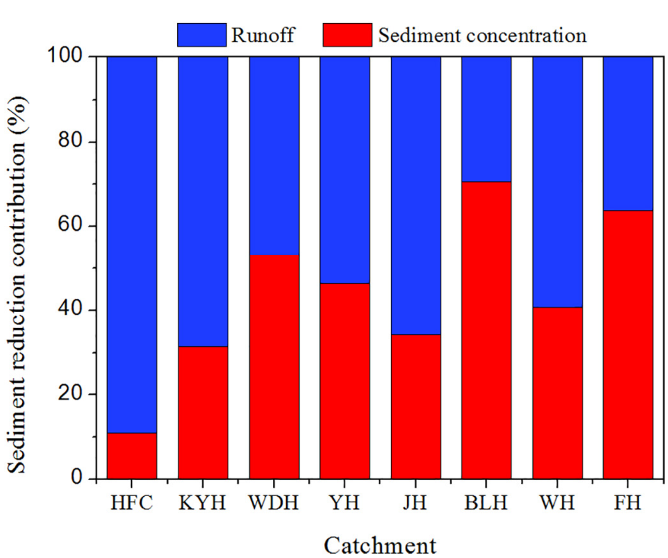

Fig. 5. Contributions of the runoff and sediment concentration variability to sediment load reduction between the P1 and P2 periods in the eight catchments.

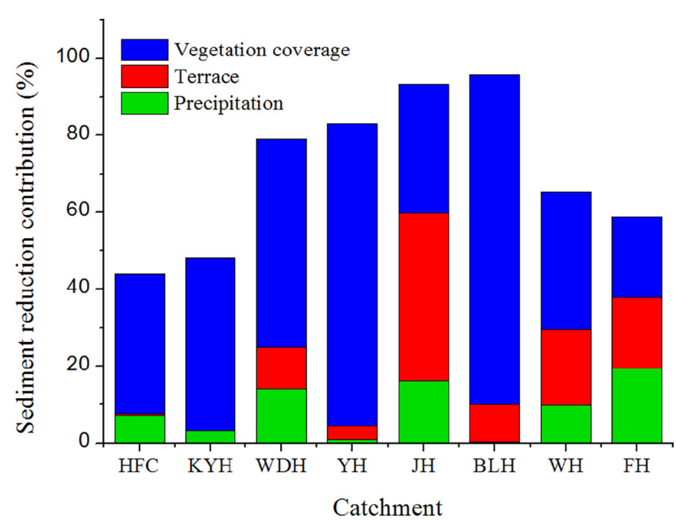

Fig. 6. Contributions of the factors to sediment load reduction between the P1 and P2 periods in the eight catchments.

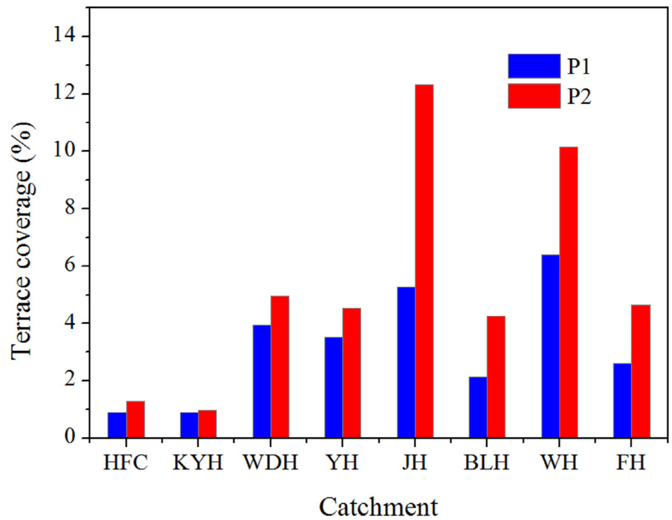

Fig. 7. Terracing as a percentage of total land area in the years 1990 and 2010 in the eight catchments.

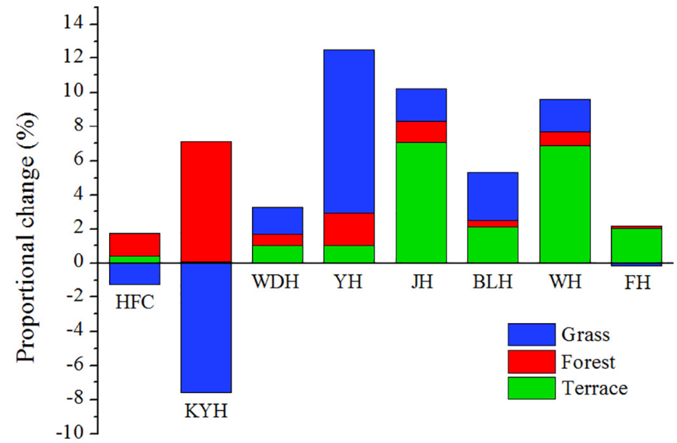

Fig. 9. The variability in grassland, forestland and terrace as a percentage of total land area from 1990 to 2010 in the eight catchments.

4. Discussion

4.1. Impacts of climate change on sediment load

Climate change impacts on soil erosion have been observed around the world, and precipitation and temperature are the dominant factors that directly influence the runoff and further affect the variation in sediment load (Nunes et al., 2013; Li and Fang, 2016; W. Wei et al., 2016; Y. Wei et al., 2016). Evidently, the stream flow and sediment load were positively correlated with the precipitation in the mainstream of the Columbia River (Naik and Jay, 2011), US Midwest (Xu et al., 2013) and Yangtze River basin (Li et al., 2016). A similar situation also appeared in eight tributaries in the middle reaches of the Yellow River, where the correlations between annual regional precipitation and sediment load are significant (Table 4). During the past five decades, the average annual precipitation of the Loess Plateau exhibited a downward trend and decreased by 1.13 $mm \cdot yr^{-1}$. Another climatic factor of temperature increased by 0.03 $°C \cdot yr^{-1}$ (Zhao et al., 2013), which increases the potential evapotranspiration and reduces the runoff and sediment load. Changes in climate change accounted for 20% of the sediment discharge reduction above the Huayuankou station during 1979–2007 (Peng et al., 2010). In our study, precipitation variety contributed to the reduced sediment load by 9.1% from P1 to P2, and the values vary mainly from 7.3 to 19.3% for catchments, which was similar to the previous research that estimated the precipitation change contribution rate was 9.0–50.3% for sediment discharge reduction since the 1970s in various regions of the Yellow River basin (Gao et al., 2011; Mu et al., 2012).

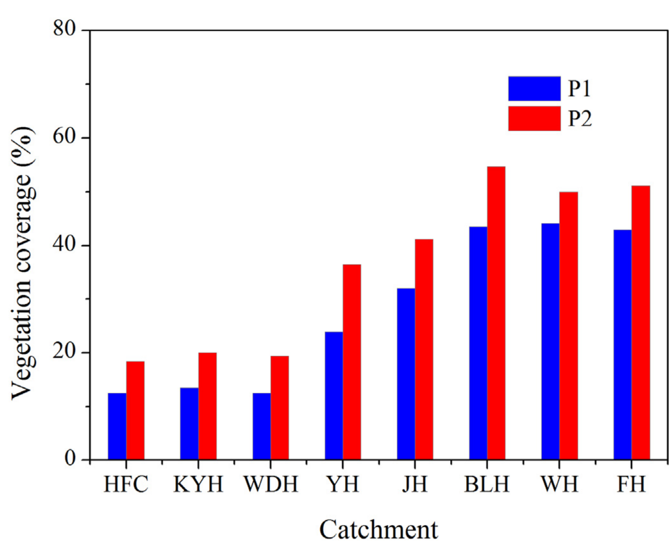

Fig. 8. Average vegetation coverage in P1 and P2 in the eight catchments.

4.2. Impacts of human activities on sediment load

Terraces were constructed on sloped agricultural fields to control soil erosion by leveling the ground surfaces and reducing the slope lengths. Evidence shows that terraces increase soil moisture, improve soil properties, and save incoming water to prevent sediment from entering the river and, eventually, to achieve the function of water and soil conservation (Syvitski and Kettner, 2011; Zhao et al., 2013). Between the Toudaoguai and Tongguan stations in the middle reaches, the area of terraces was 530 km^2 in 1959 and increased to 28,540 km^2 in 2006 (Zhao et al., 2014). Our results show that the terrace construction was mainly distributed in the Jinghe and Weihe catchments from 1990 to 2010 (increased by 4.9% and 7.0%), where the sediment load was reduced by 19.8% and 43.8%. Liu et al. (2014) found that terraces contributed to the reduced sediment load by 91.2% in 2009–2012 in the upper reaches of the Weihe River, with a terrace ratio increasing by 31.3%. Zhang et al. (2014) reported that compared to 1956–1969, the terraces could reduce the Ganguyi station sediment yield by 271×10^4 t and 374.2×10^4 t in the Yanhe catchment in 2005 and 2011, respectively, according to the SWAT model. In our study, terraces contributed to the reduced sediment load by 381.2×10^4 t in P2, which was slightly greater than the above-mentioned results. The discrepancies may be due to different lengths of the sediment load time series. The efforts to restore the ecological environment by terrace construction could be highly beneficial for control of sediment load soil and water losses. Furthermore, the 2010 to 2030 plan of comprehensive sediment treatment in the Loess

Table 4
Regression equations between annual precipitation and sediment discharge.

	Sediment discharge (10^8 $t \cdot yr^{-1}$)		
	Equation	R^2	p-Value
Huangfuchuan	0.0021Pre-0.4237	0.275	<0.01
Kuyehe	0.0047Pre-1.0126	0.253	<0.01
Wudinghe	0.0061Pre-1.4393	0.294	<0.01
Yanhe	0.0016Pre-0.3704	0.134	<0.01
Jinghe	0.0077Pre-1.5642	0.186	<0.01
Beiluohe	0.0015Pre-0.0815	0.046	0.132
Weihe	0.0029Pre-0.4868	0.072	0.025
Fenhe	0.001Pre-0.3448	0.193	<0.01

Note: Pre refers to annual precipitation.

Plateau region estimates an increase in terraces to around 2.6×10^4 km^2 (Ma et al., 2015). The role of terraces in reducing the sediment load is therefore anticipated to increase in the future.

In 1999, the Chinese government launched the GfG, which was the largest forest ecological construction project in the world and refers to steps taken to reduce/control soil erosion by converting low grain yield and unstable land to forest or grassland (Xin et al., 2012). Ten years after the implementation of the GfG, the forest and grassland increased to 2208.8 km^2 (4.4%) and 2948.7 km^2 (4.4%) in the catchments of the eight tributaries in the Loess Plateau, respectively. A simulation study for the Huangfuchuan catchment found that cropland shrinkage (−3.7%) and forestland expansion (14.7%) could reduce the sediment load (40.6%) (Zuo et al., 2016). With the increasing grass and forestland, the average vegetation coverage has increased from 28.4% in P1 to 41.4% in P2. Sun et al. (2015) reported that vegetation coverage in Yan'an (located in the Yanhe catchment) and Yulin (located in the Wuding catchment) has exhibited an overall improvement since implementation of the GfG, and the sediment transfer from this region to the Yellow River dramatically declined from 1.6 to 0.1 BT during the most recent decade (Xin et al., 2011; Zhao et al., 2013). Increased vegetation cover is an effective soil erosion control measure in the Loess Plateau by enhancing rainfall interception, weakening raindrop kinetic energy, and tapping runoff flow. However, when cultivated field or grasslands are converted to trees or shrubs, some fast-growing species may be established. The deep roots can extract underground water, reduce soil moisture, and lower the water table thereby presenting significant challenge to the survival of fast-growing plants (Asner et al., 2008; Cao et al., 2011). From 1982 to 2005, the overall tree survival rate of afforestation projects was reportedly only 24%, and due to the lack of soil moisture, most of the surviving trees were “small and old trees” in the Loess Plateau (Wang et al., 2007a). The attempts to control soil erosion by afforestation may not be so successful due to these adverse changes. Thus, we suggest that the selection of appropriate species and locations is important for maintaining a sustainable vegetated ecosystem and sediment load reduction.

To have a better understanding, the impacts of terrace construction and large-scale vegetation restoration projects on sediment load, changes in soil erosion intensity are shown in Fig. 10. It can be noted that the spatial distribution of severe erosion change is concentrated in the upstream regions of Beiluhe and Yanhe and in the middle and lower reaches of Wudinghe and Huangfuchuan, whereas the regions of intensive and very intensive change mainly occur in the hills and mountainous regions with a very steep slope (Fig. 10). For all study catchments in the Loess Plateau, the soil erosion showed a decrease. From 1990 to 2010, the erosional area reduced by 5.4×10^4 km^2 in the entire studied catchments, which is a reduction of 39.8% and the erosional area with a greater intensity reduced by 60.0%. The success of the slope soil protection is an important reason for reducing the amount of sediment entering the river. Among the main tributary catchments, the Jinghe was the most successful in soil conservation with a reduction of 49.5% in the erosional area and 75.2% in the greater intensity area. The increase in terraces and vegetation coverage in the Jinghe catchment are notable factors in the drastic erosion decline, and the subsequent sediment load reduction by 63.2%. Soil conservation measures on the slope were critical to the sediment discharge reduction during P2.

The check dams built in the gullies or channels to trap sediments from upstream have been effective measures to control sediment discharge (Porto and Gessler, 1999; Mekonnen et al., 2015). Over the past 50 years, approximately 110,000 check dams were built in the Loess Plateau (Jin et al., 2012), including 6942 key dams (storage capacity $>50 \times 10^4$ m^3), of which sediment has filled 33.7 Gm^3 of these dams and 60,000 moderate and small dams (storage capacity $<50 \times 10^4$ m^3) in the middle reaches of the Yellow River. Most of the check dams are located in the northern catchments such as the Huangfuchuan, Kuyehe, Wudinghe, and Yanhe. Taking the Huangfuchuan as an example, among

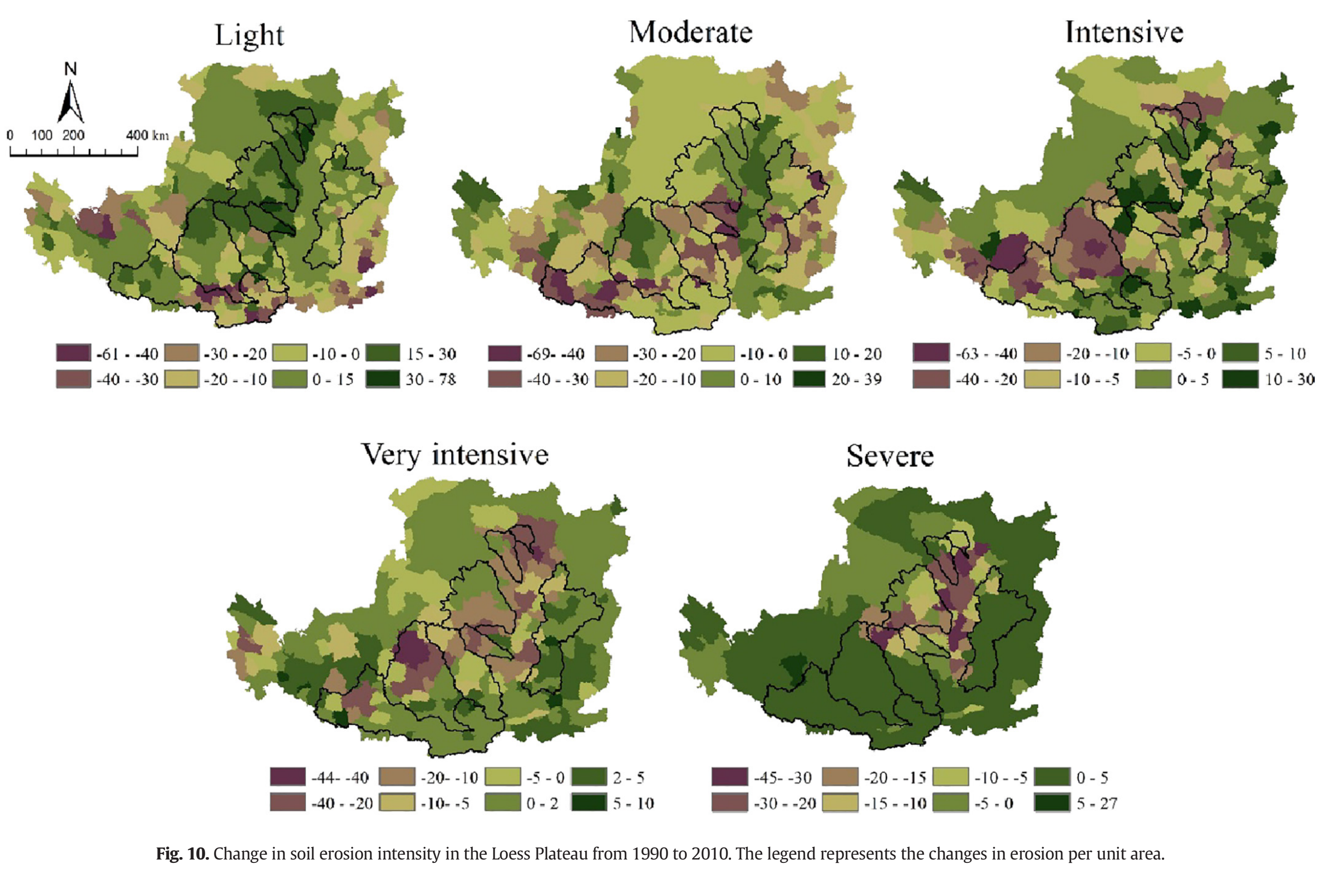

Fig. 10. Change in soil erosion intensity in the Loess Plateau from 1990 to 2010. The legend represents the changes in erosion per unit area.

507 dams in the catchment, nearly 90% of them were built after 1970, which controlled approximately 70% of the catchment and has cumulatively trapped 232.7 Mm^3 of sediment over the past 50 years (Tian et al., 2013). There are also approximately 2500 reservoirs situated in the Loess Plateau. The Xiaolangdi reservoir trapped 2.1×10^8 $Mg \cdot yr^{-1}$ of sediment recently. For the middle reaches of the Yellow River, based on to the number of reservoirs and dams and their trapping rates, Wang et al. (2015) found that check dams and reservoirs seem to account for 12% (reduced to 0.29 $Gt \cdot yr^{-1}$) of the total reduction from P1 (1980–1998) to P2 (1999–2010). Check dams and reservoirs effectively reduce the sediment discharge in the Loess Plateau. However, dams and reservoirs should have immediate and substantial trapping effects on runoff and sediment load reductions, and these structures do not represent a sustainable long-term method of sediment control because of rapid filling. Reinforcement of check dams and replacing the slow filling sediment trapping dams should be addressed in the future.

4.3. Implications for sediment load reduction

Our results demonstrated that the sediment load changes in the Loess Plateau catchments were mainly controlled by human activities at the beginning of the 21st century. The annual sediment discharge has been regulated to historic levels, such as those before around 600 CE (Chen et al., 2015). This change has been achieved by the engineering structures such as dams and reservoirs, agricultural engineering such as terraced farming, biological engineering such as large-scale land use change with the GfG, of which vegetation recovery has reduced the sediment load the most since 1999. For catchments, the dominant factor for sediment load reduction was different. For example, dams play a decisive role in reducing sediment discharge in the Huangfuchuan catchment. However, check dams alone do not represent a sustainable long-term method of sediment control. Thus, several check dams along with restoration of vegetation should be a sustainable management strategy for long-term soil and water conservation (Gao et al., 2016; Zhao et al., 2017). Vegetation recovery was dominant in reducing sediment discharge in the Beiluohe catchment, where preventing vegetation degradation and maintaining a sustainable vegetated ecosystem is critical for the future. For the Yellow River basin, soil and water conservation measures comprehensively affect the runoff and sediment discharge. Optimizing space allocation for these measures is still a challenge and this needs to be addressed in future work. Further, hydrological models with engineering measure modules should be developed to simulate the relationship between climate change, human activities, and sediment discharge to manage the health of watersheds.

5. Conclusions

In our study, eight catchments located in the Loess Plateau were chosen to investigate the trends in sediment discharge since the 1960s. Then, the relative contributions of climate variability and human activities to sediment discharge were evaluated using attribution approaches. The annual rate of sediment discharge decrease ranged from -0.007 to -0.039 $Gt \cdot yr^{-1}$ for all eight catchments. Specifically, the total annual sediment loads of all gauging stations exhibited decreasing trends ($p < 0.0001$) of -0.180 $Gt \cdot yr^{-1}$. The double mass curves between the sediment load and precipitation indicate abrupt drops in sediment load around the year 1996 in all tributaries. The sediment load changes were divided into two periods covering 1980 to 1996 (P1) and 1997–2012 (P2). A dramatic decrease in sediment discharge occurred from P1 to P2, and all catchments were reduced by >40% mainly due to human activities. The increase in perennial vegetation coverage and terrace farming accounted for 66.3% of the sediment load reduction in tributaries during P1 and P2, while climate factors accounted for 9.1%. Different measures are used to control the soil erosion in the catchments, and terraces play a dominant role in sediment retention in the Jinghe, whereas vegetation coverage was the main reason for sediment reduction in the Yanhe.

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